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ENGINEERING SERVICES FOR THE NEXT GENERATION NUCLEAR PLANT (NGNP) WITH HYDROGEN PRODUCTION

Test Plan - Power Conversion System Equipment for a Direct Combined Cycle

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1 INTRODUCTION

The NGNP Power Conversion System (PCS) testing outlined in this plan is for a combined gas turbine and steam cycle. The major components considered here include the turbocompressor and associated generator (see Figure 1 and Figure 2). The testing required to address the design data needs of the steam generator is outlined in a separate NGNP test plan. Subcomponents, such as electromagnetic bearings, turbine blades, generator insulation, and seals, are discussed in this test plan. These subcomponents may tested by the turbomachinery vendors or by suppliers to the turbomachinery vendors before major component integration.

1.1 Scope

This PCS Test Plan outlines the design and test processes for NGNP PCS Final Design.

1.2 Purpose

The purpose of the testing outlined in this test plan is to verify the operation of the PCS turbomachinery hardware consisting of the generator, turbine, and compressor. Therefore, this can be viewed as a succession of integration tasks, assuring the functionality of subsystems and subcomponents as they are integrated together for seamless operation.

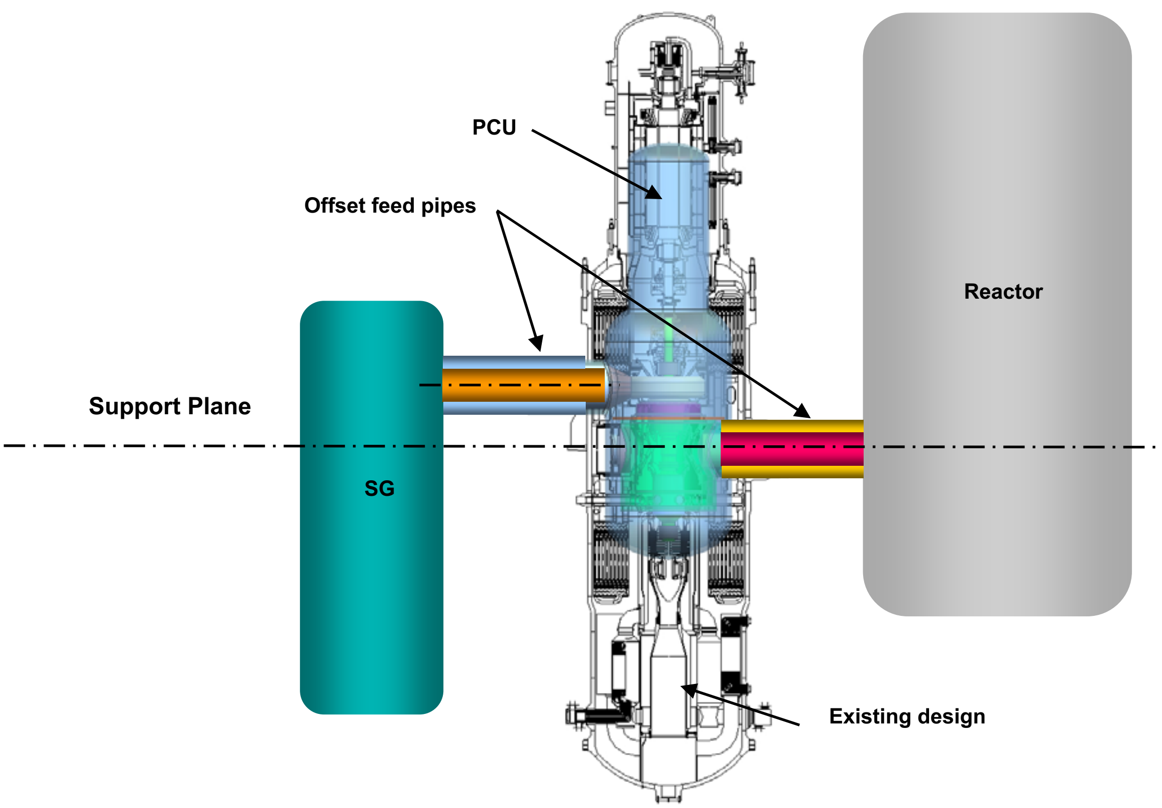


Figure 1. General Layout of Proposed Alternative Direct Combined Cycle NGNP

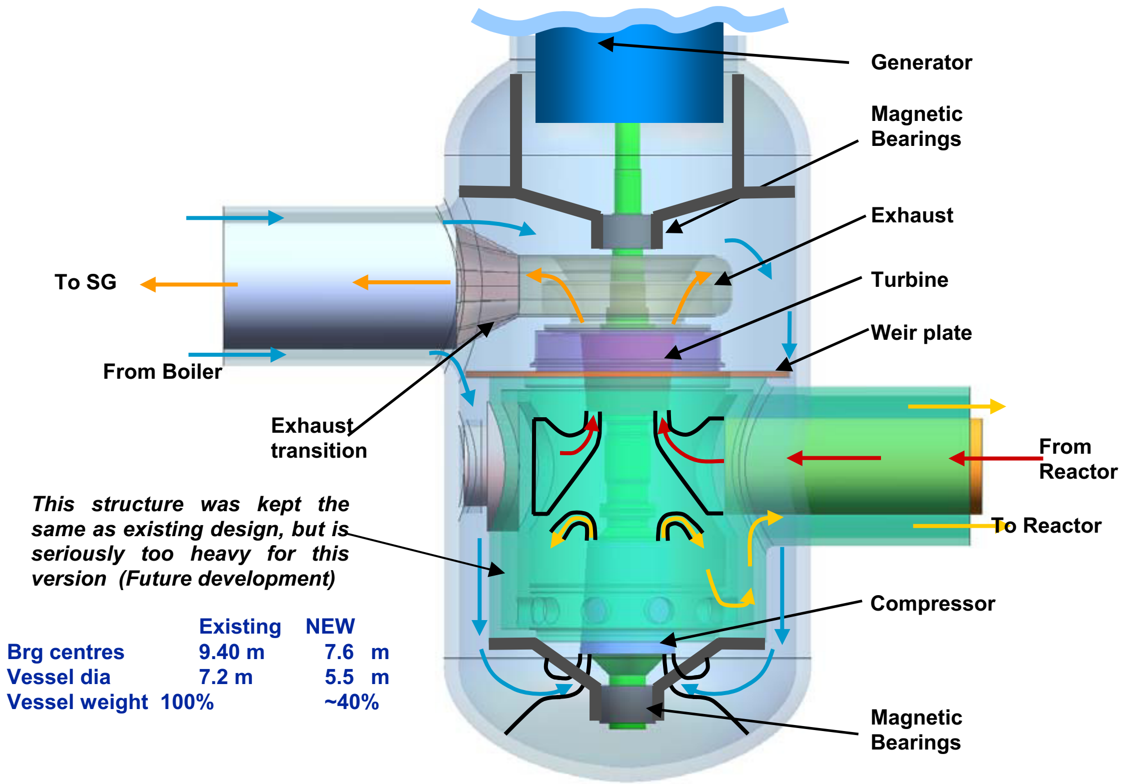


Figure 2. General Layout of Proposed Alternative Direct Combined Cycle PCS

1.3 PCS Component Testing Classification/Breakdown

Table 1. PCS Component Classification/Breakdown

TRL Current Rating	Components to be Tested			TRL Rating to be Achieved
TRL 4	Generator[1]	Turbine[1]	Compressor[1]	TRL 5
	-winding insulation samples -electrical lead-out strength	-aerodynamics -rotating seals -electromagnetic bearings (EMBs) -catcher bearings (CBs)	-verify the material embrittlement in helium[3] -no self-welding of materials[3] -stage performance[3]	
TRL 5	Generator[2]	Turbine[2]	Compressor[2]	TRL 6
	-insulation dielectric at op conditions[3] -lead-outs performance at op conditions[3]	-aerodynamics, rotating seals, EMBs, and CBs at op conditions[3]	-stage performance at less than optimal speeds at op conditions[3] -acoustic load[3]	
TRL 6	Generator	Turbocompressor (TC)		TRL 7
	-full-scale model testing at ambient air conditions	-full-scale model testing at ambient temp and pressure (air) conditions		
TRL 7	Turbomachinery (TM)			TRL 8
	-full-scale, integrated turbine, compressor, and generator test. Operate at operations temp and He pressure conditions, followed by event conditions.			

(1) Testing possibly to be conducted by manufacturer.

(2) The difference in testing performed between TRL levels 4-5 and 5-6 is that the TRL tests 4-5 will be conducted in air at ambient conditions and TRL tests 5-6 will be conducted at operating temperatures and helium pressures.

(3) Compressor tests to be included in future revisions of this Test Plan.

2 APPLICABLE DOCUMENTS

Table 2. Applicable NGNP PCS Documents

Document Number	Title
TDPP_Aug06	Power Conversion Unit Technology Demonstration Program Plan, Experimental Design Bureau of Machine Building (OKBM), Nizhny Novgorod, Russia, 2005
DNS133534 v1.0	Preliminary Assessment of the GT-MHR Power Conversion System, Rolls-Royce Inc, July 10, 2007
PC-000396	PC-MHR Engineering Development Plan, General Atomics, November 20, 1995
PC-000543	Preconceptual Engineering Services for the Next Generation Nuclear Plant (NGNP) with Hydrogen Production, NGNP Umbrella Technology Development Plan”, General Atomics, July 2007

3 TRL 4 TO 5 – PCS COMBINED CYCLE SUBCOMPONENT TESTING AT STP[1]

3.1 TEST: Generator Winding Insulation and Electrical Lead-Out Testing

3.1.1 Generator Winding Insulation and Electrical Lead-Out Test Objectives

The operation of the generator within a closed pressurized helium system required the development of high-voltage, high current electrical penetrations of the helium pressure boundary. Electrical insulation commonly used in generators operating in air will have inferior dielectric properties in the helium environment.

The dielectric characteristics of the electrical generator insulation at various temperatures, at various loads, operating in a pressurized helium environment. The generator electrical leads are also tested at similar operating environments, so the test set-up may be similar and shared.

Electrical generator insulation and lead-out testing is necessary to verify the properties of insulations (thermal and ceramic) in a high temperature helium environment over the lifetime of the generator.

3.1.2 Generator Winding Insulation and Electrical Lead-Out Test Description

Samples of insulation will be tested in an environmental test chamber at elevated temperatures with available high-voltage, high-current power supplies. Electrical feedthroughs similar in design to the concentric electrical lead-out assemblies should be installed on the environmental test chamber, typically on a spoolpiece flange.

Although testing at this TRL level movement from TRL 4 to TRL 5 will begin testing in air at elevated temperatures, the TRL 5 to TRL 6 tests, described in Section 4.1, will immediately begin upon completion of insulation testing in air, once the environmental chamber is pumped down and back filled with helium. Rapid helium depressurization of the environment and thus the insulation will also be tested as part of the TRL 5 to TRL 6 effort, simulating a loss of helium coolant in the reactor.

3.1.3 Generator Winding Insulation and Electrical Lead-Out Test Conditions

Test are expected to be conducted as bench-scale (environmental chamber) at this TRL level 4 to TRL 5 at standard temperature and pressure. The insulation dielectric testing is a first step, as testing in air will lead to a different dielectric effect that testing in a helium environment. The lead-out testing will begin at low power in air.

---

[1] *Standard air Temperature and atmospheric Pressure*

3.1.4 Generator Winding Insulation and Electrical Lead-Out Test Configuration

Samples of insulation should be placed in the test chamber at the environmental test facility. Electrical lead-outs should be installed on the environmental chamber feedthrough flange. The environmental chamber should have a purge valve to simulate a loss of helium coolant rapid depressurization.

The environmental chamber should be capable of the following [PCU TDPP]:

- Helium supply as the chamber backfill gas
- Working pressure: 0.1 to 2.66 MPa (atmospheric to 384 psi)
- Maximum pressure: 11.6 MPa (1,680 psi)
- Depressurization: 0.3 MPa/sec (43.5 psi/sec)
- Helium temperature: 20-100°C
- Insulation sample temperature: 170°C maximum (heater tape into chamber)
- Voltage supply: 20 kV maximum at 10 kA

3.1.5 Generator Winding Insulation and Electrical Lead-Out Test Duration

A range of temperatures, pressures, and voltages (from standard atmospheric temperature and pressure to maximum of temperature, pressure, and voltage) should all be applied during the test. Helium entrainment within the insulation will be a life cycle issue and will be only qualitatively discussed in Section 4.1.

3.1.6 Generator Winding Insulation and Electrical Lead-Out Possible Test Locations

Generator winding insulation and electrical lead-out testing, for TRL 4 through TRL 6, will be conducted in an environmental test facility. Environmental test facilities can easily accommodate temperature and pressure simulations, but not all facilities may have the power supply for the 20kV maximum voltage.

Environmental test facilities can be found in regional, industrial areas. Just as an example, the southern California region offers the environmental test facilities below. As the NGNP testing progresses and is funded, closer collaboration with these facilities will be necessary to confirm, mainly, access to the power supply to conduct the lead-out testing.

NORTHROP GRUMMAN (formerly TELEDYNE RYAN)
http://www.st.northropgrumman.com/capabilities/SiteFiles/docs/Experimental_Test_Facility.pdf
Alternative test facility location:
Unmanned Systems Development Center
Integrated Systems

Northrop Grumman Corporation
17066 Goldentop Road
San Diego, CA 92127
(858) 618-4462
Ed Everett or Steve Ballmer

REMEC, Inc.
9404 Chesapeake Drive
San Diego, CA 92123
(858) 560-1301 or (858) 505-3183
Gilbert Groves
Ggroves@remec.com

NATIONAL TECHNICAL SYSTEMS (NTS)
http://www.ntscorp.com/
1536 East Valencia Drive
Fullerton, CA 92831-4734
(800) 677-2687
NTS provides integrated engineering services and technical solutions, product testing and design for compliance, regulatory standards compliance testing and evaluation, project management, technical resources, engineering solutions and managed services. NTS is globally accredited by many leading regulatory agencies. NTS has testing laboratories and engineering services offices located in North America, Europe and Asia. NTS is the largest independent testing laboratory in the world.

3.1.7 Generator Winding Insulation and Electrical Lead-Out Measured Parameters

The electrical insulation dielectric constant and degradation when exposed to elevated temperatures should be determined. Later, degradation should be determined when exposed to operation in helium environment. Mechanical strength of lead-out insulation should be determined. Potential stand-off testing (hi-potting) should be performed on the electrical feedthrough to determine rated standoff voltages in air can be achieved. In Section 4.1, lead-out standoff voltages will be verified in the helium environment.

3.1.8 Generator Winding Insulation and Electrical Lead-Out Data Requirements

The data generated from the insulation and lead-out testing should meet QA Level II requirements.

3.1.9 Generator Winding Insulation and Electrical Lead-Out Test Evaluation Criteria

Voltage data will be recorded to determine the dielectric strength of the insulation and the stand-off potential of the lead-out assemblies. Other test parameters, such as insulation and lead-out temperatures and chamber pressure, will also be recorded. These values will be compared to expected values to determine insulation and lead-out performance. Witnessing the test and instrumentation of the test specimens (insulation and lead-out) will verify no breakdown in the electrical insulation or the lead-out electrical isolation. If, during testing and post-processing of test data, the voltage results vary more than 10% -15% from expected values, results discrepancies should be investigated.

3.1.10 Generator Winding Insulation and Electrical Lead-Out Test Deliverables

At a minimum, a record of the following will be necessary at the conclusion of testing:

- Detailed discussion of test method
- Equipment employed
- Equipment calibration verification
- Detailed test procedures
- Original test data
- Summarized and reduced test data
- A detailed discussion of test results, observations, and calculations that were completed throughout the course of testing.

Electrical insulation and lead-out samples should be stored in an inert environment to allow for additional testing.

3.1.11 Generator Winding Insulation and Electrical Lead-Out Cost, Schedule, and Risk

Test costs are summarized in Table 3. The schedule is summarized in
Figure. Both costs and schedule are contained within the Generator Test Category.

It is essential that these subcomponent insulation and lead-out tests be completed. Modeling may not properly simulate the insulation effects, especially the helium diffusion in the insulation. Once the helium permeates the insulation, rapid helium depressurization can cause damage to the insulation. Damage to the insulation after helium depressurization will need to be determined in a follow-on test following the depressurization of the test chamber.

3.2 TEST: Turbine Aerodynamics Performance (DDN C.41.00.01)

Turbine aerodynamics tests are expected to be conducted at this TRL 4 to TRL 5 at standard temperature and pressure. The possible test locations outlined in Section 3.2.6 will simulate the operating environments for development to support turbine aerodynamics TRL 4 through TRL 6. The scope of this combined cycle turbine includes operation at a maximum temperature of 850°C at 5000 rpm. Shaft speeds of 3600 rpm, 4400 rpm, and 5000 rpm were analyzed [Rolls Royce 07]. Inlet temperatures greater than 850°C require turbine blade cooling from the circulating helium, thus reducing the overall plant efficiency. This requires further optimization studies.

3.2.1 Turbine Aerodynamics Performance Test Objective

Turbine aerodynamics need to be tested to verify turbine design computer models and the efficiency at operating temperature. Iteration may be necessary to optimize design and test for turbine optimization performance. An outcome of the testing should verification of the combined cycle turbine design, which includes [Rolls Royce 07]:

- Understanding of turbine material limitations
- Turbine efficiency optimization
- Diffuser integration
- Feasibility of blade height designs
- Blade, shroud, and platform mass
- Blade root feasibility
- Disk and overall rotating mass

3.2.2 Turbine Aerodynamics Performance Test Description

To accommodate the testing to be performed for turbine development from TRL 4 through TRL 6, a turbine test rig should have capability to test the turbine aerodynamics in air (TRL 4-5) and later aerodynamics testing in helium (TRL 5-6). The test rig should be a closed heated loop, able to operate at various air and helium pressures (see Section 3.1.4 for test parameters).

3.2.3 Turbine Aerodynamics Performance Test Conditions

The turbine testing should simulate operating conditions. The combined cycle turbine operating conditions are [Rolls Royce 07]:

- Thermal Power Rating: 66 MW
- Mass Flow: 280 kg/s
- Shaft Speed: 5,000 rpm
- Inlet Total Pressure: 7,020 kPa
- Inlet Total Temperature: 850°C
- Outlet Total Pressure: 3,760 kPa
- Outlet Total Temperature: 620°C

3.2.4 Turbine Aerodynamics Performance Test Configuration

As has been noted with the compressor model stage testing outlined in [PCU TDPP], page 53, the turbine model for testing and iterative optimization with design may be fabricated at 1:5 scale. This scale size should be verified.

The turbine test loop is a helium loop capable of heating and pressurization as listed in Section 3.2.3 test conditions.

3.2.5 Turbine Aerodynamics Performance Test Duration

The production turbine design life is 60,000 hours (~6.8 years) [PCU TDPP]. The test duration will be a subset of that time, enough to assure turbine designers that effects such as creep at steady state temperatures.

3.2.6 Turbine Aerodynamics Performance Possible Test Locations

The test location URLs listed below each show multiple test facility locations. For this turbine aerodynamics performance testing, and for turbomachinery testing that follows when the technology is further developed, these test facilities are large such that they may be equipped to accommodate the full-scale turbomachinery. The gas facilities may or may not currently include a helium loop (except for PBMR listed below); this should be explored once the NGNP program engages with the test facilities. These facilities may be in addition to the facilities offered by the vendor chosen to supply the turbine.

SIEMENS
http://www.powergeneration.siemens.com/products-solutions-services/service/corrective-preventive-maintenance/repairs/factories_service_centers/

GENERAL ELECTRIC (GE)
http://www.gepower.com/businesses/ge_oilandgas/en/literature/en/downloads/testing_capabilities.pdf

HELIUM TEST FACILITY at PBMR
The PBMR project has built test facilities along with the power plant construction. The Helium Test Facility currently has multiple on-going tests.
http://www.pbmr.co.za/index.asp?Content=230

3.2.7 Turbine Aerodynamics Performance Measured Parameters

Inlet and outlet pressures, inlet and outlet temperatures, helium mass flow, shaft speed, and overall calorimetry to determine turbine efficiency should be measured. Thermocouples, pressure sensors and transducers, mass flow sensors and transducers, and shaft speed sensor data should all be recorded for post-test analysis.

3.2.8 Turbine Aerodynamics Performance Data Requirements

Testing should meet QA Level II requirements where test results could impair, but not prevent, normal operating performance. Tests are relevant to components outside of the reactor containment and are not considered safety-related.

3.2.9 Turbine Aerodynamics Performance Test Evaluation Criteria

Data recorded during tested must be post-processed and reviewed for inconsistent or inaccurate findings. The data must show that the turbine had reached steady-state operation such that no further temperature rise would occur with continued operation. Creep life is typically the limiting factor of turbine design [Rolls Royce 07, Pg. 45]. In order to achieve a design life of 60,000 hours at 850°C (or program-chosen maximum temperature), the TRL 4-5 test should simulate turbine operational rotation speeds. Later testing (in Section 4.2.9) will require operating and design basis temperatures and pressures to verify that creep and creep fatigue is within acceptable design limits.

3.2.10 Turbine Aerodynamics Performance Test Deliverables

At a minimum, a record of the following will be necessary at the conclusion of testing:

- Detailed discussion of test method
- Equipment employed
- Equipment calibration verification
- Detailed test procedures
- Original test data
- Summarized and reduced test data
- A detailed discussion of test results, observations, and calculations that were completed throughout the course of testing.

3.2.11 Turbine Aerodynamics Performance Cost, Schedule, and Risk

Test costs are summarized in Table 3. The schedule is summarized in

Figure. Both costs and schedule are contained within the Turbocompressor Development Category.

It is essential that these turbine aerodynamic performance tests be completed. Modeling may not properly simulate turbine operation, so testing will be used to verify modeling.

3.3 TEST: Turbocompressor Rotating Seals

Seal tests may be conducted in collaboration with seal manufacturers. Seals discussed in this section refer to the stator seals.

3.3.1 Turbocompressor Rotating Seals Test Objective

Turbocompressor stator seals are designed to minimize the helium leakage between the stator annular cavities. The seals must allow for turbocompressor removal approximately every 60,000 hours (6 to 8 years). The seals must allow for relative movement between sealing surfaces in the axial and radial directions due to temperature changes and dynamic deformations. The seals will also compensate for any distortion (out-of-tolerance or out-of-roundness) of the turbocompressor surfaces.

3.3.2 Turbocompressor Rotating Seals Test Description

Seal testing for the GT-MHR in Russia is for seals sized to fit the GT-MHR turbocompressor stator. The seals for the combined PCS cycle components may be smaller in diameter, but the temperature demands and helium environment remain the same.

The seal mockup test description has been documented [PCU TDPP]. For the combined PCS cycle seals, sliding seals with the same materials and geometries as the GT-MHR program should be used.

The seals, high-pressure air supply, high-pressure helium supply, rough vacuum pump, heater tape, and hardware machined to simulate the turbocompressor stator will be needed for the test. Sensors and instrumentation to detect operating temperatures and pressures will be fed into data acquisition equipment.

3.3.3 Turbocompressor Rotating Seals Test Conditions

For TRL 4 to TRL 5 testing, the seal test setup will be at room temperature and have a supply or pressurized air. Even at standard temperature and pressure, the following seal characteristics are tested:

- Blind installation of seals mounted on turbocompressor such that the seals may sustain damage. Ways to detect and monitor seal damage via inspection should be included.
- Seal leakage control.
- Seal reliability for the 60,000 hr expected operating life.
- Seal reliability upon enduring vibration from turbocompressor operation

3.3.4 Turbocompressor Rotating Seals Test Configuration

For the TRL 4 to TRL 5 testing, the seals will separate different air-pressured zones in the hardware, created by the seals. Four seals will be needed to separate the higher-pressure zone between two lower-pressure zones. The low pressure zones are located in the hardware above and below the pressurized central air cavity. At this time, seal isometric drawings are taken from the GT-MHR layout.

3.3.5 Turbocompressor Rotating Seals Test Duration

A major technical concern is the seal self-welding which can occur between dry helium surfaces. Seal endurance testing should be held (for TRL 4 to TRL 5, in air, followed by TRL 5 to TRL 6 in helium). Wear of protective coatings should be monitored during endurance testing.

3.3.6 Turbocompressor Rotating Seals Possible Test Locations

Timken Bearing is a large manufacturer of bearings and seals as well as many other products and technical services. Although Timken is not explicitly listed as a nuclear supplier, Timken is a good reference for design of the seals.

OKBM
Gas seal test facility.
http://www.iaea.org/inisnkm/nkm/aws/htgr/fulltext/htr2004_e29.pdf

TIMKEN BEARING
http://www.timken.com/en-us/products/seals/industrial/Pages/default.aspx

3.3.7 Turbocompressor Rotating Seals Measured Parameters

- Determine damage upon blind installation into assembly
- Measure seal leakage (for air in TRL 4.to TRL 5 and for helium in TRL 5 to TRL 6)
- Seal leakage under elevated temperatures (TRL 5. to TRL 6)

3.3.8 Turbocompressor Rotating Seals Data Requirements

Testing should meet QA Level II requirements where test results could impair, but not prevent, normal operating performance. Tests are relevant to components outside of the reactor containment and are not considered safety-related.

3.3.9 Turbocompressor Rotating Seals Test Evaluation Criteria

For the GT-MHR program, the limit of helium leakage shall not exceed 0.41% of the helium coolant flow through the reactor [PCU TDPP – page 63]. The seals must reach a steady state operating temperature not to exceed the operating temperatures limits of the seal material.

3.3.10 Turbocompressor Rotating Seals Test Deliverables

At a minimum, a record of the following will be necessary at the conclusion of testing:

- Detailed discussion of test method
- Equipment employed
- Equipment calibration verification
- Detailed test procedures
- Original test data
- Summarized and reduced test data
- A detailed discussion of test results, observations, and calculations that were completed throughout the course of testing

3.3.11 Turbocompressor Rotating Seals Cost, Schedule, and Risk

Stator seal test estimates are included in Table 3 and

Figure. Seals' cost and schedule are both included contained within the Turbocompressor Development Category.

3.4 TEST: Turbocompressor Bearings

Bearing tests may be conducted in collaboration with bearing manufacturers. Bearings classification includes the electromagnetic bearings (EMSs) and catcher bearings (CBs).

3.4.1 Turbocompressor Bearings Test Objectives

The EMBs and CBs are magnetic bearing and are considered a significant project risk, which is minimized by using the combined PCS cycle where the turbocompressor and generator are smaller due to the steam generator operating in parallel. EMB design may incorporate a diaphragm coupling between the turbocompressor and the generator rotor, depending upon if the combined cycle PCS is modeled after the GT-MHR PCS in this regard.

An important part of this scaled EMB testing is the verification of the rotor dynamics analysis program and control software. Operation of the EMB test through critical shaft speeds is important to determine EMB control system response. In addition to these operational characteristics, testing should verify:

- Support static weight of the turbocompressor and generator
- Support dynamic weight of the turbocompressor and generator while in operation
- EMB rotor control
- Reliability
- Friction wear
- Maintainability
- Condition monitoring
- Installation and maintenance

3.4.2 Turbocompressor Bearings Test Description

The EMB consists of the stator, a rotor, and rotor position sensors. The tests should include:

- Radial EMB model test setup with control system
- EMB position sensor
- Rotor dynamics model
- Rotor scale model

3.4.3 Turbocompressor Bearings Test Conditions

The EMBs are attached to a central axis on the test rig to accommodate scaled bearing assemblies. Tests for TRL 4 to TRL 5 are conducted in air at room temperature. Figure 3 through Figure 7 show drawings, photographs, and sample data of the EMB bearing test set-ups. A rotor, stator, and electromagnetic bearing are built in a scaled model test facility. Radial and axial displacement sensors, turning angle sensor, and thermocouples are included in the test setup.

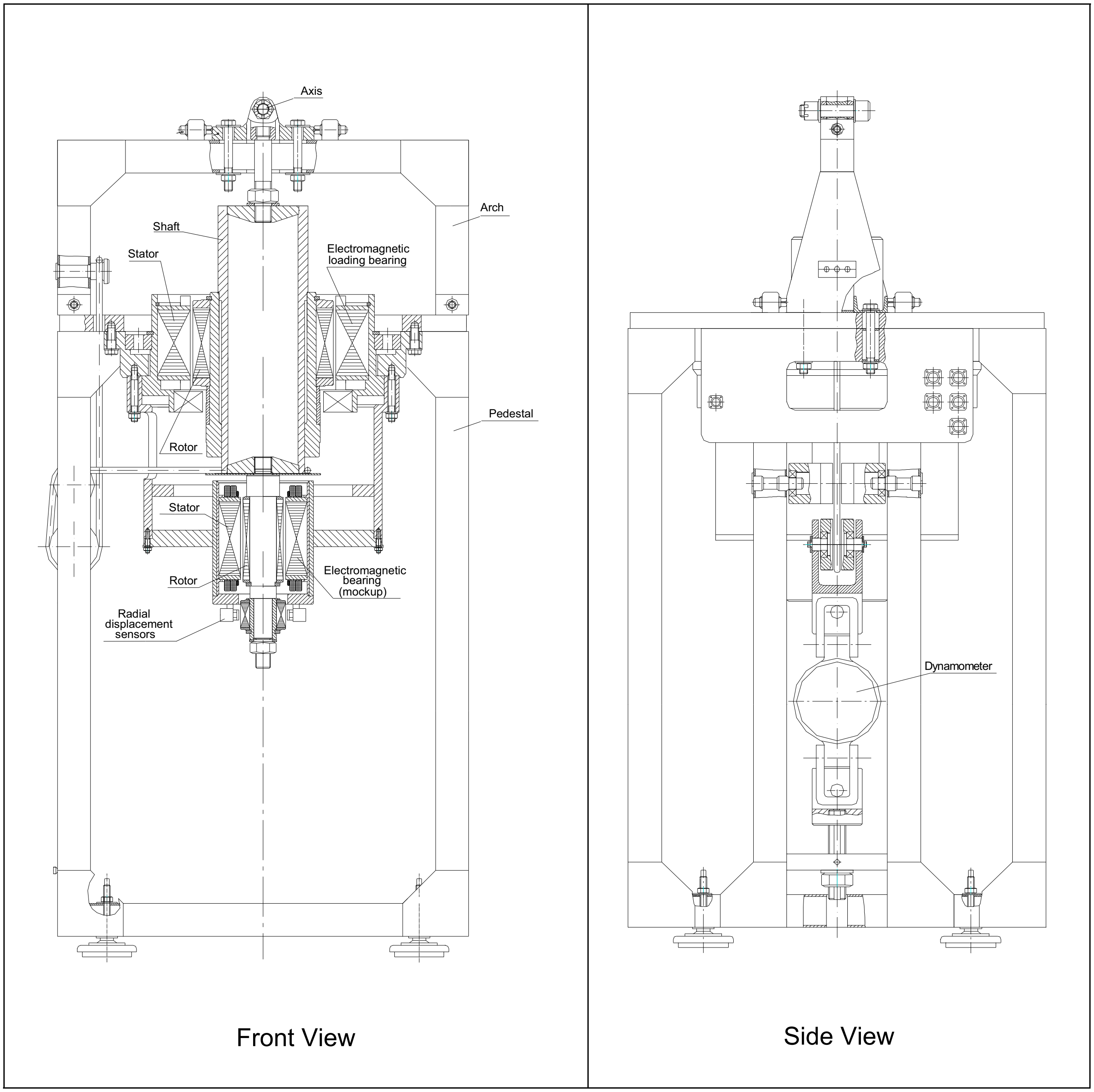


Figure 3. Radial EMB Test Facility Schematics [PCU TDPP]

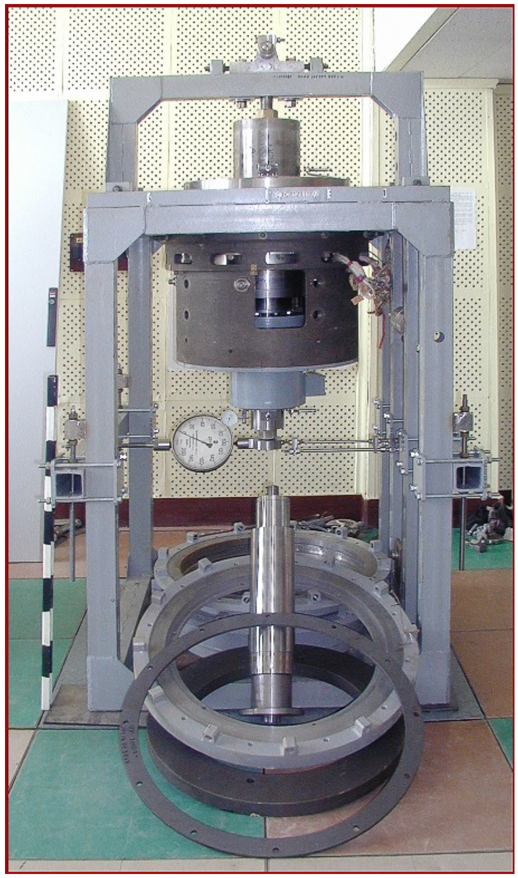


Figure 4. Radial EMB Model Test Facility [PCU TDPP]

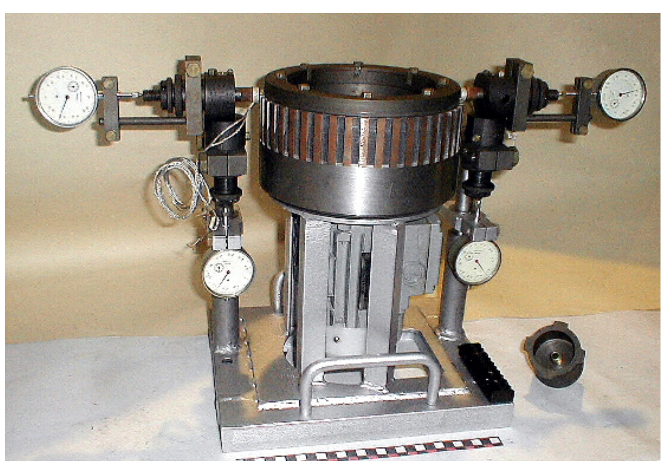
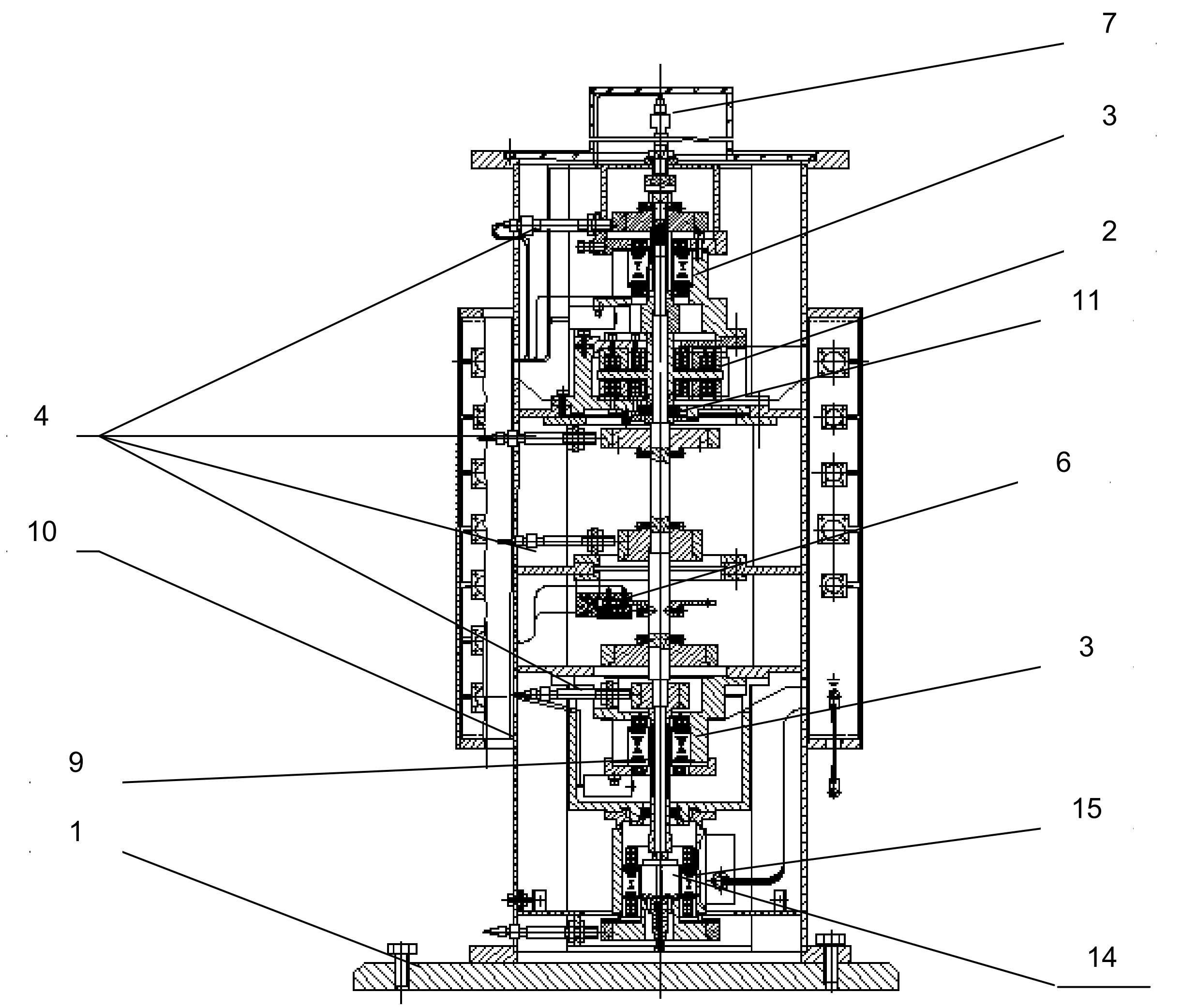
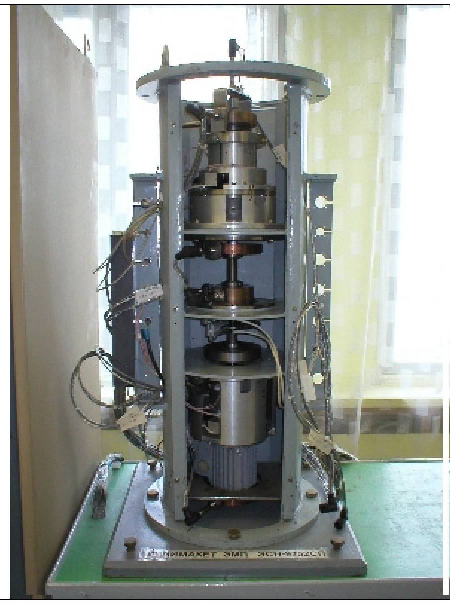


Figure 5. EMB Sensor Test Rig [PCU TDPP]



1 - support plate	6 – turning angle sensor	11 – radial/axial CB
2 – axial EMB	7 – axial displacement sensor	12 – rotor
3 – radial EMB	8 – axial sensor rotor part	13 – radial EMB
4 – radial displacement sensor	9 – radial CB	14 – motor rotor part
5 – radial CB	10 – casing	15 – motor stator

Figure 6. Electromagnetic Support Suspension System Test Schematic with Vertical Rotor
[PCU TDPP, reference Minimockup Tests]



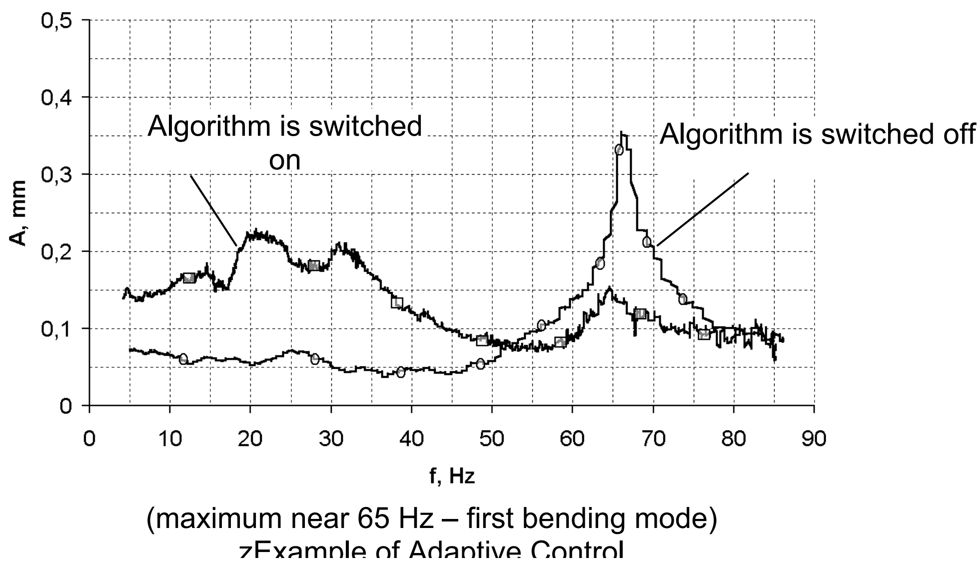


Figure 7. Electromagnetic Support Suspension System Test Setup and Adaptive Control Data

3.4.4 Turbocompressor Bearings Test Duration

Since the purpose of this TRL 4 to TRL 5 EMB testing is to witness EMB operation to verify dynamics analysis and control system response, the test should be conducted until adequate data is collected to support the dynamics analysis verification and to pass through several critical shaft speeds to witness control system response.

3.4.5 Turbocompressor Bearings Possible Test Locations

The possible EMBs test locations listed below are further described in the references.

OKBM [PCU TDPP]

S2M [Rolls Royce 07]

SKF (formerly known as REVOLVE) [Rolls Royce 07]

WAUKESHA (formerly GLACIER) [Rolls Royce 07]

SYNCHRONY [Rolls Royce 07]

3.4.6 Turbocompressor Bearings Measured Parameters

The following, at a minimum, should be measured during EMB testing:

- Shaft speeds
- Critical shaft speeds
- Axial and radial bearing loads
- Radial and axial displacement
- Turning angle

3.4.7 Turbocompressor Bearings Data Requirements

Testing should meet QA Level II requirements where test results could impair, but not prevent, normal operating performance. Tests are relevant to components outside of the reactor containment and are not considered safety-related.

3.4.8 Turbocompressor Bearings Test Evaluation Criteria

EMB testing may move onto to testing for TRL 5 to TRL6 if it is determined that the dynamics models have accurately predicted the scaled EMB operation and that there is no excessive radial and axial movement, especially as the stator passes through critical speeds.

3.4.9 Turbocompressor Bearings Test Deliverables

At a minimum, a record of the following will be necessary at the conclusion of testing:

- Detailed discussion of test method
- Equipment employed
- Equipment calibration verification
- Detailed test procedures

- Original test data
- Summarized and reduced test data
- A detailed discussion of test results, observations, and calculations that were completed throughout the course of testing

3.4.10 Turbocompressor Bearings Cost, Schedule, and Risk

Bearing test estimates are included in Table 3 and Figure 9. Bearing test' cost and schedule are included in the EM Bearings Test Category.

4 TRL 5 TO 6 – PCS COMBINED CYCLE SUBCOMPONENT TESTING AT OPERATING TEMPERATURE AND HELIUM PRESSURE

4.1 TEST: Generator Winding Insulation and Electrical Lead-Out Testing

4.1.1 Generator Winding Insulation and Electrical Lead-Out Test Objectives

Continue the testing initiated for generator winding insulation and electrical lead-out described in Section 3.1. These test will now include operating environmental conditions such as elevated temperature and operation in a helium environment including simulated helium impurities expected in primary loop flow.

In addition, during normal operation at working pressure, helium will diffuse in the electrical insulation. A rapid depressurization would cause the helium to expand, possibly causing damage to the insulation. Rapid helium depressurization will be tested in this series of continued insulation and lead-out tests.

4.1.2 Generator Winding Insulation and Electrical Lead-Out Test Description

See Section 3.1.2.

4.1.3 Generator Winding Insulation and Electrical Lead-Out Test Conditions

See Section 3.1.3

4.1.4 Generator Winding Insulation and Electrical Lead-Out Test Configuration

See Section 3.1.4.

4.1.5 Generator Winding Insulation and Electrical Lead-Out Test Duration

See Section 3.1.5

4.1.6 Generator Winding Insulation and Electrical Lead-Out Possible Test Locations

See Section 3.1.6.

4.1.7 Generator Winding Insulation and Electrical Lead-Out Measured Parameters

The insulation dielectric constant and insulation degradation when exposed to operating environment, and the effects on the electrical leads will be determined.

4.1.8 Generator Winding Insulation and Electrical Lead-Out Data Requirements

See Section 3.1.8.

4.1.9 Generator Winding Insulation and Electrical Lead-Out Test Evaluation Criteria

See Section 3.1.9

4.1.10 Generator Winding Insulation and Electrical Lead-Out Test Deliverables

At a minimum, a record of the following will be necessary at the conclusion of testing:

- Detailed discussion of test method
- Equipment employed
- Equipment calibration verification
- Detailed test procedures
- Original test data
- Summarized and reduced test data
- A detailed discussion of test results, observations, and calculations that were completed throughout the course of testing

4.1.11 Generator Winding Insulation and Electrical Lead-Out Cost, Schedule, and Risk

Test costs are summarized in Table 3. The schedule is summarized in Figure 9. Both costs and schedule are contained within the Generator Test Category.

It is essential that these subcomponent insulation and lead-out tests be completed. Modeling may not properly simulate the insulation effects, especially the helium diffusion in the insulation. Once the helium permeates the insulation, rapid helium depressurization can cause damage to the insulation. Damage to the insulation after helium depressurization will need to be determined in a follow-on test following the depressurization of the test chamber.

4.2 TEST: Turbine Aerodynamics Performance (DDN C.41.00.01)

The turbine aerodynamic testing was initiated during testing during development for TRL 4 to TRL 5. This test is a continuation of those test where the testing at standard temperature and pressures will now be conducted at elevated expected operating temperatures and at operating helium pressures.

4.2.1 Turbine Aerodynamics Performance Test Objectives

See Section 3.2.1.

4.2.2 Turbine Aerodynamics Performance Test Description

See Section 3.2.2.

4.2.3 Turbine Aerodynamics Performance Test Conditions

See Section 3.2.3.

4.2.4 Turbine Aerodynamics Performance Test Configuration

See Section 3.2.4.

4.2.5 Turbine Aerodynamics Performance Test Duration

See Section 3.2.5.

4.2.6 Turbine Aerodynamics Performance Possible Test Locations

See Section 3.2.6.

4.2.7 Turbine Aerodynamics Performance Measured Parameters

See Section 3.2.7.

4.2.8 Turbine Aerodynamics Performance Data Requirements

See Section 3.2.8.

4.2.9 Turbine Aerodynamics Performance Test Evaluation Criteria

See Section 3.2.9.

4.2.10 Turbine Aerodynamics Performance Test Deliverables

See Section 3.2.10.

4.2.11 Turbine Aerodynamics Performance Cost, Schedule, and Risk

Test costs are summarized in Table 3. The schedule is summarized in Figure 9. Both costs and schedule are contained within the Turbocompressor Development Category.

It is essential that these subcomponent turbine aerodynamic tests be completed. Modeling may not properly simulate the turbine aerodynamics, so the test results are needed to compare against the modeling predicted performance.

4.3 TEST: Turbocompressor Rotating Seals

The turbocompressor rotating seals testing for TRL 4 to TRL 5 represent the beginning of the overall testing for the full development of the seals in preparation for incorporation into the integrated designs. The rotating seals testing will continue with all operating parameters invoked, such as elevated temperatures and helium pressures.

Sections 3.3.1 through 3.3.11 all apply to Sections 4.3.1 through 4.3.11 below.

4.3.1 Turbocompressor Rotating Seals Test Objectives

See Section 3.3.1.

4.3.2 Turbocompressor Rotating Seals Test Description

See Section 3.3.2.

4.3.3 Turbocompressor Rotating Seals Test Conditions

See Section 3.3.3. For the testing at operating and design basis temperatures and helium pressures another test condition is:

- Seal operating requirements, such as helium at 510°C and a pressure drop of 0.03 MPA to 4.6 MPa across the seal. Design basis events should be included, such as elevated temperatures and pressures.

4.3.4 Turbocompressor Rotating Seals Test Configuration

See Section 3.3.4.

4.3.5 Turbocompressor Rotating Seals Test Duration

See Section 3.3.5.

4.3.6 Turbocompressor Rotating Seals Turbine Rotating Seals Possible Test Locations

See Section 3.3.6.

4.3.7 Turbocompressor Rotating Seals Measured Parameters

See Section 3.3.7.

4.3.8 Turbocompressor Rotating Seals Data Requirements

See Section 3.3.8.

4.3.9 Turbocompressor Rotating Seals Test Evaluation Criteria

See Section 3.3.9.

4.3.10 Turbocompressor Rotating Seals Test Deliverables

See Section 3.3.10.

4.3.11 Turbocompressor Rotating Seals Cost, Schedule, and Risk

See Section 3.3.11.

4.4 TEST: Turbocompressor Bearings

Just as in Section 4.3 above, the testing for the turbocompressor electromagnetic bearings (EMBs) and catcher bearings (CBs) TRL 5 to TRL 6 is the same as all details listed in Sections 3.4.1 through 3.4.10 with the exception of testing operations at elevated temperatures and helium pressures. The test description elements will not be duplicated here.

5 TRL 6 TO 7 – INTEGRATED PCS TURBOCOMPRESSOR AND GENERATOR TESTING AT STP[1]

To achieve the next level of PCS Turbomachinery development, TRL 7, all elements in Section 4, TRL 5 to 6, have been successfully completed. Turbomachinery operating at normal conditions (in air at ambient temperature and pressure) is next.

5.1 TEST: Generator and Turbocompressor Fabrication and Integration

The generator and turbocompressor should be fabricated and tested at this level in the program. There is likely that there will be more than one manufacturer for this equipment, so a common location for integration is needed.

At this point in the program, no specific generator testing has been conducted. Vertical generators are used in the hydroelectric industry, including a vertical generator with a 35 ton rotor, so the generator risk is considered minimal. This combined cycle PCS has the advantage of deploying a smaller electrical generator, which reduces program risk and increases possibility for an off-the-shelf generator design.

In order to reduce testing costs, it is proposed to construct and integrate full scale turbomachinery components and complete all testing for TRL 6 through TRL 8. Section 5 outlines testing for taking the fabricated turbomachinery components, assembling the components in the test facility, and perform system checkout in air. Section 6 outlines integrated testing of the turbomachinery components at operating temperature in the helium environment.

5.1.1 Generator and Turbocompressor Fabrication and Integration Test Objectives

- Check the manufacture, assembly, and mounting of the generator and turbocompressor
- Adjustment of the EMB control system in air with suspension of the turbocompressor rotor on the EMBs
- Check generator and turbocompressor operation in air with the turbocompressor driven by a motor in the test facility
- Validation of procedures for installation, alignment, and balancing of turbocompressor motors
- Integrated performance of the full-scale EMB support system
- EMB control of rotor dynamics with integrated installation
- Validation of catcher bearing rundown capabilities
- Validation of vertical generator design
- State-by-stage speedup of turbocompressor using test facility motor to the maximum allowable rotation speed in air, followed by decrease in turbocompressor rotor to stopping while monitoring rotor behavior through resonant frequencies.

- Check change-over to catcher bearings when EMBs are de-energized
- Verify non-excessive vibration (vibration dampening during operation)
- Verify that blind installation for stator seals is acceptable, and that in-service seal inspection is possible
- Verify gaps between rotating and stationary turbocompressor parts
- Forward-looking validation of procedures for removal, repair, or replacement and reinstallation of turbomachinery components, scheduled to occur every 7-8 years.

5.1.2 Generator and Turbocompressor Fabrication and Integration Test Description

This begins the testing of the integrated turbine, compressor, and generator, the major components of the combined cycle PCS. This full-scale test will not require a nuclear heat source – an electric heater will be used to heat the helium stream. The shaft load on the turbocompressor will be simulated by a motor in the test facility. To enable steady-state and operational testing, described in Section 6, the turbomachinery will operate in a closed helium gas loop.

5.1.3 Generator and Turbocompressor Fabrication and Integration Test Conditions

Full-scale turbomachinery equipment, for TRL 6 to TRL 7 testing, will be conducted in air at ambient temperature.

5.1.4 Generator and Turbocompressor Fabrication and Integration Test Configuration

Test facility will require:

- Large concrete structure to support turbomachinery, simulating power plant cavity where the actual turbomachinery will be installed, to test seals and reactions of rigid support structure to handle static and dynamic load of turbomachinery and support equipment.
- Motor used to drive the turbomachinery rotor.
- Heater capable of heating helium stream to 850°C and cooler to simulate helium inlet and outlet operating temperatures.

5.1.5 Generator and Turbocompressor Fabrication and Integration Test Duration

- Perform operational testing in air such that rotational speeds from 0% to 120% of nominal rotation speed is tested.
- Testing such that all test objectives in Section 5.1.1 have been witnessed and successfully completed.

5.1.6 Generator and Turbocompressor Fabrication and Integration Possible Test Locations

The testing may be conducted at the either the generator manufacturer's facility, turbine, or compressor manufacturer's facility. Manufacturers such as Rolls Royce, Howden, General Electric, Mitsubishi Heavy Industries, may be candidate manufacturers with test facilities. However, the manufacturers may not have sufficient test facilities to perform the integrated turbomachinery tests without making significant investment. Other potential test facility locations are listed below, realizing that only basic test infrastructure may be at these locations, not a full capacity helium test loop.

NORTHROP GRUMMAN
http://www.st.northropgrumman.com/capabilities/SiteFiles/docs/capistrano/FETS_brochure_1.0.pdf

http://www.st.northropgrumman.com/capabilities/SiteFiles/docs/capistrano/VETS_brochure_1.0.pdf

TRANSCANADA TURBINES
http://www.tcturbines.com/default.aspx?cid=95&lang=1

MILCON P-104 GAS TURBINE TEST FACILITY
http://www.dt.navy.mil/wavelengths/archives/000036.html

5.1.7 Generator and Turbocompressor Fabrication and Integration Measured Parameters

Similar to the Turbocompressor Test Facility Flow Diagram shown in Figure 8, not including the sensors and valve signal lines for the precooler and intercooler (part of the GT-MHR direct cycle design), there are approximately 150 thermocouples, pressure sensors, flow meters, and solenoid valves installed in the test facility that need to be recorded in a data acquisition system. In addition, rotor speed and EMB axial and radial movements need to be measured. Control system input and response will also need to be recorded to determine behavior of rotor dynamic control.

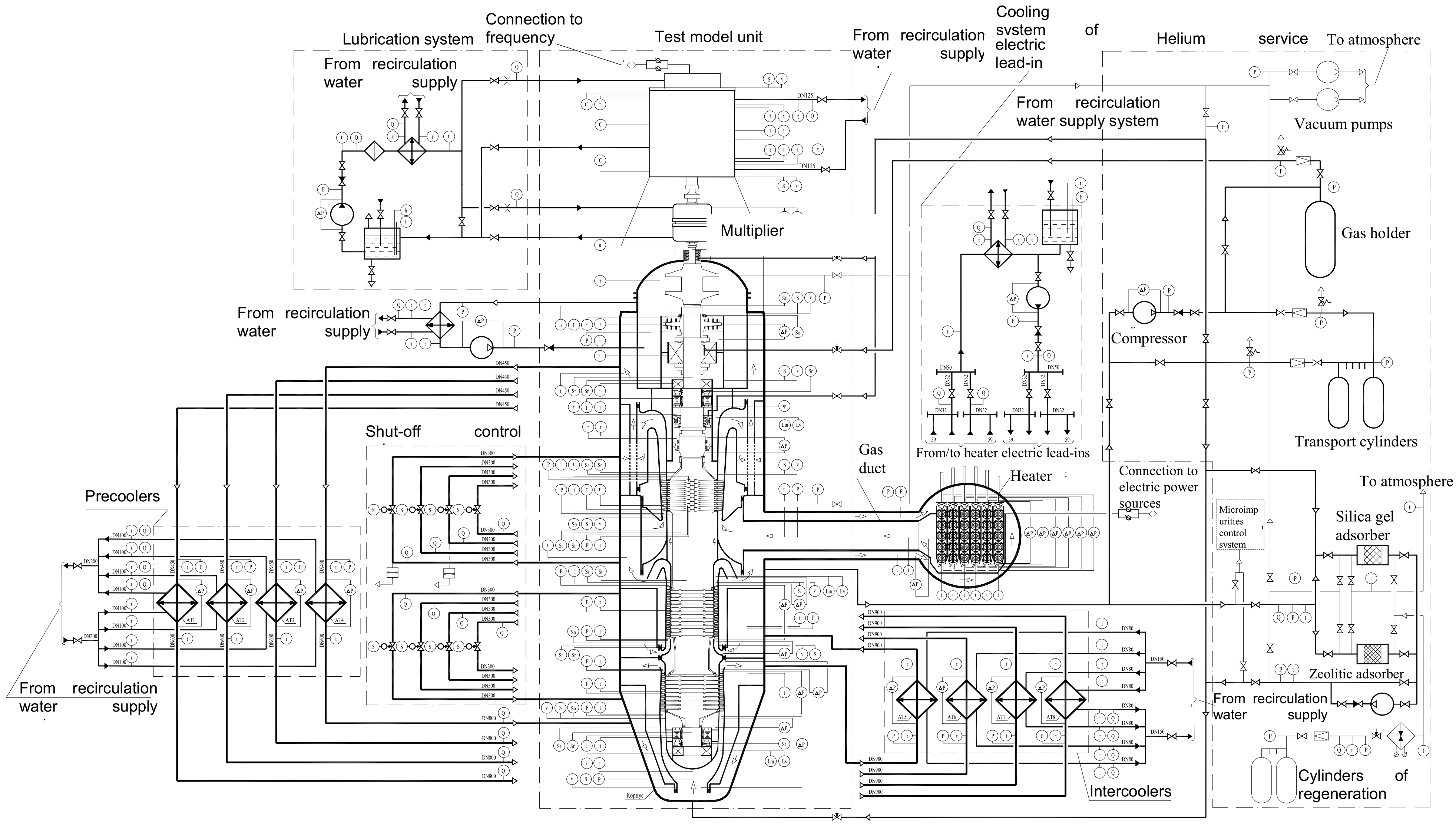


Figure 8. Turbocompressor Test Facility Flow Diagram [PCU TDPP]

5.1.8 Generator and Turbocompressor Fabrication and Integration Data Requirements

Testing should meet QA Level II requirements where test results could impair, but not prevent, normal operating performance. Tests are relevant to components outside of the reactor containment and are not considered safety-related.

5.1.9 Generator and Turbocompressor Fabrication and Integration Test Evaluation Criteria

The results of the turbomachinery testing must have successful results of all objectives listed in Section 5.1.1 in order to achieve a TRL 7.

5.1.10 Generator and Turbocompressor Fabrication and Integration Test Deliverables

At a minimum, a record of the following will be necessary at the conclusion of testing:

- Detailed discussion of test method
- Equipment employed
- Equipment calibration verification
- Detailed test procedures
- Original test data
- Summarized and reduced test data
- A detailed discussion of test results, observations, and calculations that were completed throughout the course of testing

5.1.11 Generator and Turbocompressor Fabrication and Integration Cost, Schedule, and Risk

Integration testing estimates are included in Table 3 and Figure 9. Integrated testing' cost and schedule are included in the test category TC and Generator Full Scale Testing.

6 TRL 7 TO 8 – INTEGRATED PCS FULL SCALE TURBOMACHINERY TESTING

To achieve the next level of PCS Turbomachinery development, TRL 8, all elements in Sections 2 through 5 in this test plan must have been successfully completed. Operating full-scale turbomachinery for steady state and transient performance in helium at elevated temperature, with load changes, and pressurized and depressurized shutdown Design Basis Events (DBEs) is next. Helium impurities expected in the primary loop operation should also be included during TRL 7-8 testing.

6.1 TEST: Full-Scale PCS Integrated Turbomachinery Helium Testing

Operation of the PCS and all of its subsystems at normal and off normal conditions should be conducted. The equipment will be heavily instrumented to review for proper operation. Operations will begin at 50% load and gradually increase to 100% load. Transients leading to shutdown sequences have been determined for various trip events and should be verified that controlled shutdown processes follow procedure.

6.1.1 Full-Scale PCS Integrated Turbomachinery Helium Test Objectives

- Verify gas-dynamic and thermal performance of the turbocompressor
- Turbocompressor acoustics are within acceptable range
- Control for turbomachinery transient events, notably over-speed
- Assure EMB operation over all rotor speeds
- Verify vibration and acoustic characteristics are within acceptable limits at all speeds
- Verify gas dynamic characteristics at decreased pressures
- Asssure proper gaps between turbomachinery stationary and rotating equipment at operating temperatures
- Verify smooth EMB to CB changeover when EMBs are de-energized
- Assure that equipment temperatures are not rising during simulated steady-state operation
- Measure displacements of rotor and stator elements during operation to assure migration of major components does not exceed limits
- Verify that the limit of helium leakage through stator seals is not exceeded

6.1.2 Full-Scale PCS Integrated Turbomachinery Helium Test Description

See Section 5.1.2.

6.1.3 Full-Scale PCS Integrated Turbomachinery Helium Test Conditions

Full-scale turbomachinery equipment, for TRL 7 to TRL 8 testing, will be conducted in helium at elevated temperatures to simulate operating temperatures. Test conditions will also simulate transient and Design Basis Event conditions.

6.1.4 Full-Scale PCS Integrated Turbomachinery Helium Test Configuration

See Section 5.1.4. The same test facility is planned for the TRL 6 to TRL 7 testing as is this TRL 7 to TRL 8 testing.

6.1.5 Full-Scale PCS Integrated Turbomachinery Helium Test Duration

- Perform operational testing in helium at simulated operating temperatures such that rotational speeds from 0% to 120% of nominal rotation speed are tested, both in ramp-up and slow-down of rotor shaft speed.
- Enough testing such that all test objectives in Section 6.1.1 have been witnessed and successfully completed.

6.1.6 Full-Scale PCS Integrated Turbomachinery Helium Possible Test Locations

It is unlikely that the manufacturer of the turbomachinery or a test facility sized to handle full-scale turbomachinery will have a heated helium test loop, nor willing to make the effort to accommodate such testing. Full-scale turbomachinery testing may also be beyond the ability of the engineering-scale testing of the NGNP Component Test Facility. Therefore, it is proposed to perform the TRL 7 to TRL 8 PCS testing in NGNP.

6.1.7 Full-Scale PCS Integrated Turbomachinery Helium Measured Parameters

See Section 5.1.7

6.1.8 Full-Scale PCS Integrated Turbomachinery Helium Data Requirements

See Section 5.1.8.

6.1.9 Full-Scale PCS Integrated Turbomachinery Helium Test Evaluation Criteria

The results of the turbomachinery testing must have successful results of all objectives listed in Section 6.1.1 in order to achieve a TRL 8.

6.1.10 Full-Scale PCS Integrated Turbomachinery Helium Test Deliverables

At a minimum, a record of the following will be necessary at the conclusion of testing:

- Detailed discussion of test method

- Equipment employed
- Equipment calibration verification
- Detailed test procedures
- Original test data
- Summarized and reduced test data
- A detailed discussion of test results, observations, and calculations that were completed throughout the course of testing.

6.1.11 Full-Scale PCS Integrated Turbomachinery Helium Cost, Schedule, and Risk

Integration testing estimates are included in Table 3 and Figure 9. Integrated testing' cost and schedule are included in the TC Integration Test Category.

7 TECHNOLOGY MATURATION COST ESTIMATE SUMMARY AND SCHEDULE

A summary of the estimated costs and a schedule for PCS technology maturation testing is given in Table 3 and

Figure, respectively.

Table 3. Costs Estimates for PCS Testing

TRL	Test Category	Test	Test Costs (000's)
4-5	Turbo-Compressor Development	Turbine Aerodynamics Performance Testing	$8,132(1)
		Testing Turbocompressor Fabrication and Integration	
		Turbine Rotating Seals Testing	$7,922(1)
	Generator	Generator Winding Insulation and Electrical Lead-Out Testing	$4,135(1)
	EM Bearings	Bearings Testing: EMB Test Development (incl. coupling)	$10,543(1)
5-6	Turbo-Compressor Development	Turbine Aerodynamics Performance Testing	$4,062(1)
		Testing Turbocompressor Fabrication and Integration	
		Turbine Rotating Seals Testing	$7,922(1)
	Generator	Generator Winding Insulation and Electrical Lead-Out Testing	$4,135(1)
	EM Bearings	Bearings Testing: EMB Test Development (incl. coupling)	$10,543(1)
6-7	TC and Generator Full Scale Testing	Integrated Turbine/Compressor and Generator Testing	$9,963(1)
7-8	TC Integration(1)	Integrated Turbine, Compressor, and Generator Testing	$9,963(1)
		Total PCS Test Program:	$77,320(1)
TM Test Facility		If new turbomachinery test facility needs to be built	$49,414(1)

(1) Based on a Primavera schedule from the GT-MHR program, generated in 2003, updated to 2008 dollars. Costs include labor and non-labor expenses. All labor rates adjusted to a US rate of $180/hour.

Test Category Schedule	**Year (FY 20xx)**													
	08	09	10	11	12	13	14	15	16	17	18	19	20	21
NGNP Schedule[(1)]	CD		Prelim Design			NGNP Final Design								
								Site Work		Construction				
													Startup/ Testing	
Turbo-compressor Development		< = = = > TC, generator materials validation for helium												
			< = = = = = = = = = = = = = = = > shaft seals											
				< = = = = = = = = = = = = > aerodynamics performance testing										
Generator				< = = = = = > insulation and lead-outs testing										
						< = = = > generator operations testing with models								
							< = = = = = > generator build							
EM Bearings		< = = = > electromagnetic suspension system												
		< = = = > controls testing												
		< = = = > rotor testing												
		< = = = > friction tests												
			< = = = = = = = = = = = = > diaphragm coupling											
Full-scale Testing and Integration							< = = = = = > turbine and compressor builds							
									< = = = = = = = > TM integration					
								PCU Prototype Testing < = = = = = = >						

(1) [NGNP TDP] Overall NGNP Umbrella Technology Development schedule

Figure 9. PCS Testing Schedule by Test Category

8 REFERENCES

[NGNP TDP] "Preconceptual Engineering Services for the Next Generation Nuclear Plant (NGNP) with Hydrogen Production, NGNP Umbrella Technology Development Plan", General Atomics, PC-000543, July 2007.

[PC-MHR EDP] "PC-MHR Engineering Development Plan, General Atomics, PC-000396, November 1995.

[PCU TDPP] "Power Conversion Unit Technology Demonstration Program Plan", Product No. 08.03-006.01, Experimental Design Bureau of Machine Building (OKBM), Nizhny Novgorod, 2005.

[Rolls Royce 07] Preliminary Assessment of the GT-MHR Power Conversion System, DNS133534, Rolls-Royce Inc, July 10, 2007.

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